Inspiratory pause, I:E ratio and inspiratory rise time

By Alex Yartsev - 16/06/2015
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There is nothing about any of these variables in the 2023 CICM Primary Syllabus, but the "Acceptable" or "Good" trainee is able to *"describe the mechanisms by which compliance, I time and airway resistance influence tidal volume in PCV mode"*, according to the CICM WCA document ("Ventilation"). The same trainee *"describes the relationship between flow, I time, I:E ratio and the presence or absence of an inspiratory pause"*. The inspiratory pause remains unmentioned and the inspiratory rise time has never appeared in any viva or exam, presumably because the inspiratory pause is an artefact of a bygone era and the inspiratory rise time is usually set to a default setting which happens to also be ideal (i.e. the shortest one). Still, these are settings on the ventilator which anybody can adjust, and it is reasonable to expect that a person should have some understanding of what they're fiddling with.

In summary:

- The I:E ratio is the ratio of the duration of inspiratory and expiratory phases. It represents a compromise between ventilation and oxygenation.
- A normal I:E ratio is 1:2.
- All abnormal I:E ratios are uncomfortable and require deep sedation
- More inspiratory time (I:E 1:1.5 or 1:1) increases mean airway pressure, and favours better oxygenation, at the cost of CO_2 clearance.
    - The disadvantage of this is more haemodynamic instability and the possibility of gas trapping
    - Oxygenation may paradoxically worsen due to changes in pulmonary blood flow; particularly in volume-depleted patients
- More expiratory time (I:E 1:4 and higher) increases the expiratory CO_2 clearance and favours better ventilation
    - The disadvantage of this is the possibility of atelectasis
- An inspiratory pause is a period during inspiration during which flow ceases.
    - This decreases CO_2 clearance in scenarios of high airway resistance
    - In ARDS, the decreased alveolar dead space instead improves CO_2 clearance
- Inspiratory rise time is the rate at which the ventilator achieves the control variable.
    - The effect of this depends on the control variable bring targeted.
    - In pressure control ventilation, increasing rise time will decrease the peak

inspiratory flow rate
    - In volume control ventilaton, increasing rise tiome will increase the peak inspiratory pressure

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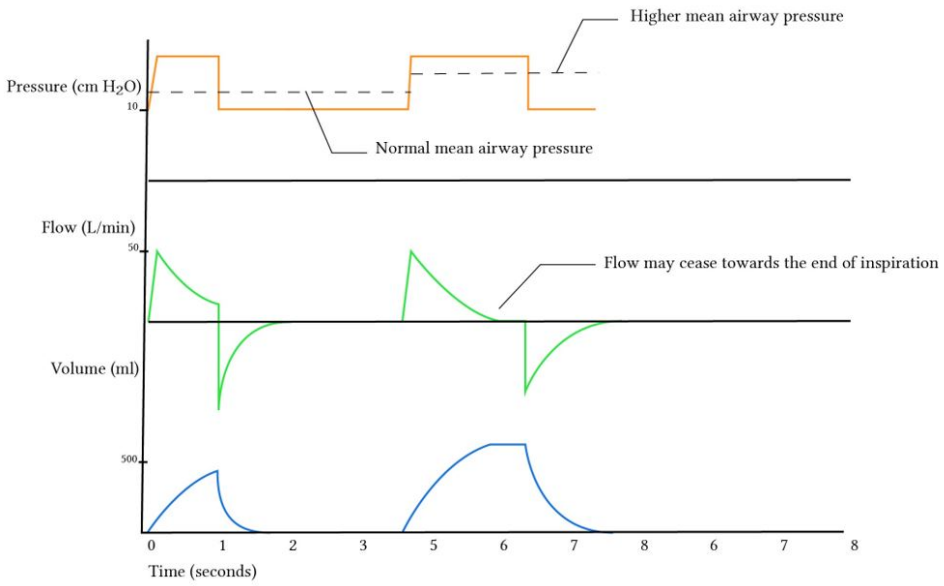
Increasing the I:E ratio to improve oxygenation

Most ventilators offer either the ability to change the absolute inspiratory time (in seconds), or the ability to change the ratio of inspiratory to expiratory time. A normal I:E ratio at rest is about 1:2, and so the default duration of the expiratory phase in mechanical ventilation is approximately twice the duration of the inspiratory phase.

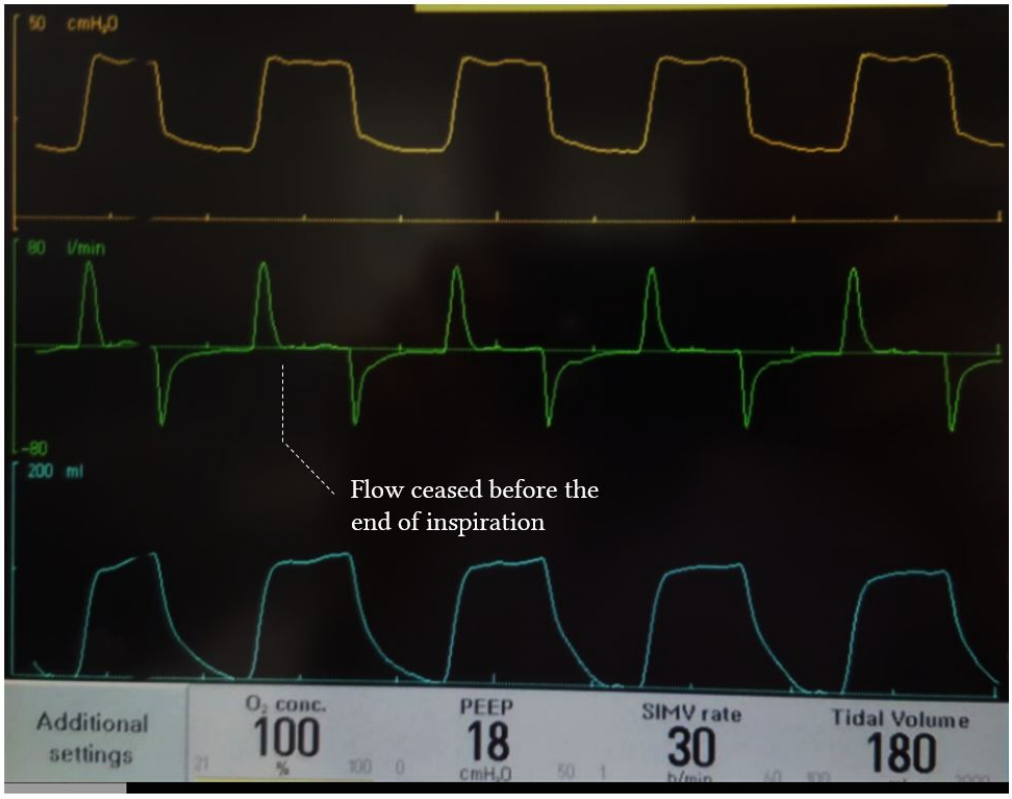
There is a theoretical benefit in increasing the I:E ratio to improve oxygenation. In general, I:E ratio to 1.5:1 or 1:1 (“equal ratio”) is in relatively routine use, whereas “inverse” ratio ventilation (using an inspiratory time which is longer than the expiratory time) is somewhat less common. For the latter, ratios up to 4:1 have been used (that’s as inverse as the SERVO-i will let you go).

Having an abnormally prolonged inspiratory time has the following expected effects:

- Increasing alveolar recruitment (by increasing mean airway pressure), thereby improving oxygenation
- Increasing the recruitment of lung units with a long time constant
- Increasing the haemodynamic effects of positive pressure ventilation by increasing the intrathoracic pressure
- Decreasing clearance of CO2 by decreasing the time available for passive expiration
- Increasing gas trapping and "auto-PEEP" by the same mechanism – i.e. this is "intentional" intrinsic PEEP.



Oxygenation being the main concern here, one can imagine that this is the strategy used in scenarios where severe hypoxia is the problem, and lung compliance is poor. As such, the volume inspired is usually quite small, and the period of air flow is short. As the result, there is an "inspiratory pause" during the inspiratory phase, where the pressure level is maintained in the absence of any flow, with a closed expiratory valve – essentially, a breath hold.

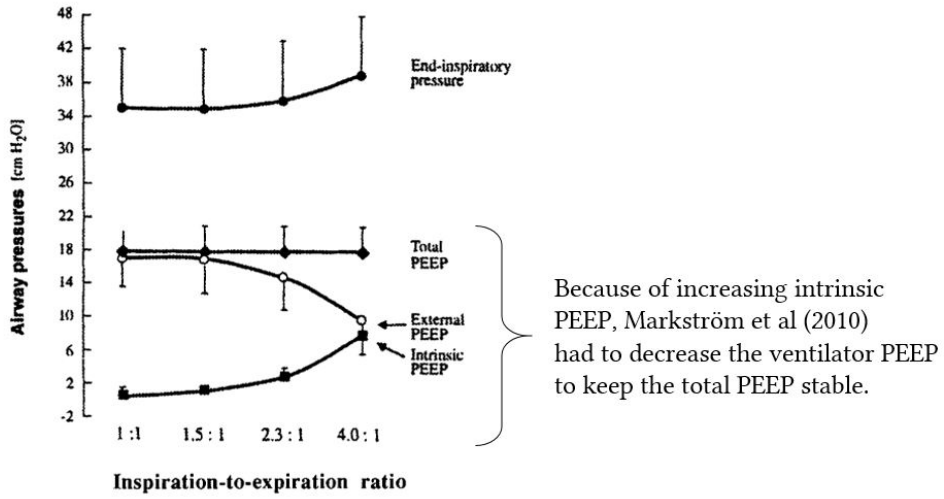


This period of zero flow has some sort of special significance, it is thought. Authors have attributed some of the mechanism of improved oxygenation to

this phase. In short, it is believed that there is improved intrapulmonary distribution of the inspired gas because the lower mean inspiratory flow allows alveoli with slow long time constants to inflate. In short, if the flow waveform has reached zero, this means two things:

1. The inspiratory time is adequate in terms of alveolar recruitment
2. Increasing the inspiratory time will not increase the tidal volume

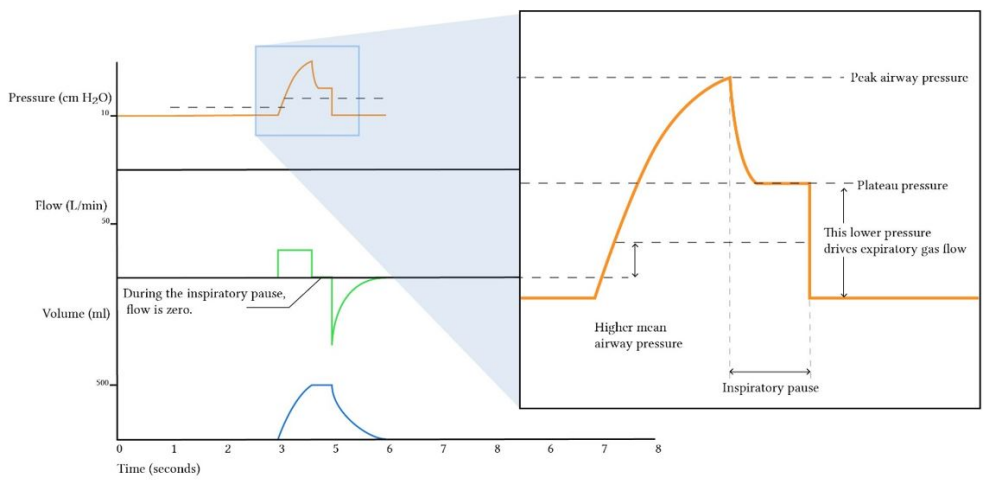
Do these theoretical concepts actually benefit patients in real life? Not always, it turns out. For example, Zavala et al (1998) used an inverse I:E ratio in ARDS, and found that oxygenation actually worsened in the short term– mainly because of the poorer pulmonary blood flow. Markström et al (2010) used I:E ratios ranging from 1:1 to a whopping 4:1 (thus, minimal expiratory time) and found a significant increase in intrinsic PEEP – so much so that they had to decrease their ventilator PEEP so as to keep the total PEEP stable. Predictably, this had an adverse effect on cardiac output: the cardiac index fell from 5.0 L/m^2 to around 3.8 L/m^2. The pressure diagram from their paper is highly instructive and is reproduced below with no modification.



In contrast, the presumably better-filled patients in the study by Kotani et al (2016) were ventilated with inverse ratios for a median duration of 10 days, and ended up doing rather well – their P/F ratios improved from 76 to over 200, with haemodynamic stability maintained throughout. Similarly, Mousa et al (2013) found improved oxygenation among bariatric surgery patients (using 1:1 ratios). Park et al (2016) broadened this to all surgical patients in a meta-analysis, and were sufficiently impressed by the short-term improvement of oxygenation.

Use of the inspiratory pause to improve oxygenation

So, if there are some oxygenation benefits from an increased time spent at a high airway pressure and zero flow, then from this it follows that any breath with such a built-in pause should have the same benefits. That was the rationale for the use of an inspiratory pause. The concept involves including a period during inspiration during which there is no flow, and the patient essentially holds their breath. This was once viewed as crucial for adequate gas exchange. Animal models (eg. Knelson et al, 1970) demonstrated an improvement in oxygenation *and* ventilation as the result of an inspiratory pause; human articles from the late 1970s such as the one by Sten Lindahl (1978) emphasised *"the importance of static end inspiratory tracheal conditions"*. The supposed improvements in oxygenation and CO_2 clearance were thought to be due to the decreased alveolar dead space.



During this inspiratory pause, there is loss of resistance due to flow throughout the airways, and there is a redistribution of pressure across the lung, which results in a total loss of elastic energy stored in the airways, lung tissue and chest wall tissue. This results in the loss of pressure within the ventilator circuit (of which the patient is a part).

This end-inspiratory positive airway pressure is what drives passive expiration once the expiratory valve is opened. So, it stands to reason that a pressure loss results in a decreased expiratory flow. If you already have some bronchospasm and your expiratory flow is already poor, and an inspiratory pause could tip you over and you could begin to trap gas, especially if the expiratory phase is

short. Oh's Manual estimates the energy loss due to inspiratory pause as 32%. This extremely specific number comes from a paper by Jonson et al (1993) which is actually an exercise in mathematically modelling the respiratory system as a Newtonian resistor. In reality nobody knows exactly how much energy is lost per second of pause and how this is influenced by the pressure which is paused at; nor is it clear that nailing this answer is going to do anybody any good. The pragmatic intensivist would angily point out that this is all bullshit and that in asthma CO2 removal benefits from the longest possible expiratory time, so why would you use anything that prolongs inspiration? This is reflected in expert recommendations such as those by Sachdev et al (2014, *Pediatric and Neonatal Mechanical Ventilation*); the authors offer to sacrifice the inspiratory pause in order to achieve a longer expiratory phase.

In contrast in ARDS the CO2 clearance is actually improved by the end-inspiratory pause. Devaquet et al (2008) found that in ARDS patients with small tidal volumes and poor compliance the introduction of a 0.7 second inspiratory pause decreased the PaCO2 by 10% after 30 minutes.

Also, it is not clear that the inspiratory pause has any positive effects on oxygenation. Fuleihan et al (1976) for example did not find any difference in oxygenation with a variety of end-inspiratory pause durations.

Lastly, there was a belief that the end-inspiratory pause somehow improved the delivery of nebulised bronchodilators, because a breath hold was considered an integral part of metered dose inhaler technique. Mouloudi et al (1998) debunked this belief by demonstrating that the effect of salbutamol was the same with or without a 5-second inspiratory pause. This makes sense, as gas flow drags nebulised medications to their site of action, and it is not clear how drug delivery would be any better in the absence of gas flow.

The influences on tidal volume in PCV

This small subheading covers the CICM WCA performance criterion where *"mechanisms by which compliance, I time and airway resistance influence tidal volume in PCV mode"* are discussed. The time-poor exam candidate may have had some difficulty finding this morsel of useful information buried in the

morass of self-indulgent gibberish, and so as not to further waste their time, here is a short summary:

- **Influence of compliance on tidal volume in PCV:**
    - Compliance is volume change per unit pressure (difference between plateau pressure and PEEP).
    - Decreased compliance during PCV will lead to decreased tidal volumes.
    - One would need to increase the inspiratory pressure to maintain the same tidal volume.
- **Influence of inspiratory time on tidal volume in PCV:**
    - The inspiratory time constant is the amount of inspiratory time required for the alveolar pressure to reach the pressure control level, and can be expressed as airway resistance multiplied by static compliance.
    - Inspiratory time should be 3-5 times the inspiratory time constant.
    - If the inspiratory time is adequate, the flow waveform will reach zero during inspiration because alveolar pressure equals control pressure (i.e. Pplat = Pinsp)
    - If the flow waveform does not reach zero, increasing the inspiratory time will increase the tidal volume.
- **Influence of airway resistance on tidal volume in PCV:**
    - Increased airway resistance will decrease the tidal volumes, because:
        - Inspiratory pressure is a sum of pressure generrated by alveolar distension and pressure generated by airway resistance
        - Thus, for a given level of total pressure, increased pressure due to airway resistance means decreased pressure spent on inflating the alveoli.
        - Also, autoPEEP will be produced, which will decrease the driving pressure (the difference between Pinsp and alveolar pressure).
    - To improve tidal volumes with PCV where the airway

resistance is high, the expiratory time needs to be decreased, or airway resistance needs to be managed medically (eg. with bronchodilators)

A good peer-reviewed resource to answer this issue is an article by Ashworth et al (2017), which describes the influences of what the authors called "forgotten but important variables". They clearly use Drager machines where they work, judging by the appearance of their ventilator graphics (similarly, the authors' own SERVOcentric tendencies are clearly demonstrated by the colour scheme of the waveforms used in Deranged Physiology).

Relationship between flow, I time, I:E ratio and inspiratory pause

Focusing more directly on the CICM WCA document, to describe"the relationship between flow, I time, I:E ratio and the presence or absence of an inspiratory pause" is a somewhat nebulous demand, which nonetheless needs to be satisfied by the Adequate trainee. For one, unlike the other performance criterion, it does not specify that which mode is being discussed. In general it is difficult to determine exactly what is expected here. One can only assume that the people dutifully ticking that box understand the college's intentions very clearly and precisely, otherwise how could they embark on the marking process.

Out of attachment to completeness, one may try to unravel the performance criteria and produce a reasoned response. At risk of repeating some of the things already mentioned:

- **Flow decreases during inspiration in PCV**
    - If flow reaches zero, the I:E ratio is optimised to deliver the maximum tidal volume; this means one can safely decrease the I:E ratio without compromising volume.
- **Flow is constant during inspiration in VCV**
    - The I:E ratio changes the necessary flow rate: decreasing inspiratory time increased the flow needed to deliver the control volume.

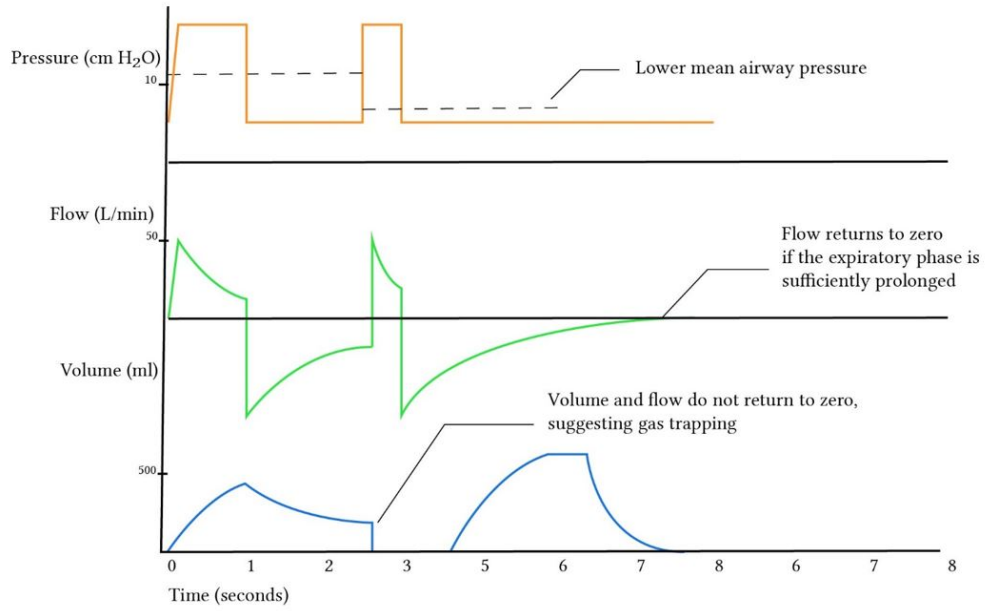
    - If there is an inspiratory pause, the inspiratory flow drops to zero; introducing an inspiratory pause means the inspiratroy flow needs to be yet again higher.
    - An inspiratory pause decreases the expiratory air flow.

Decreasing the I:E ratio to improve CO_2 clearance

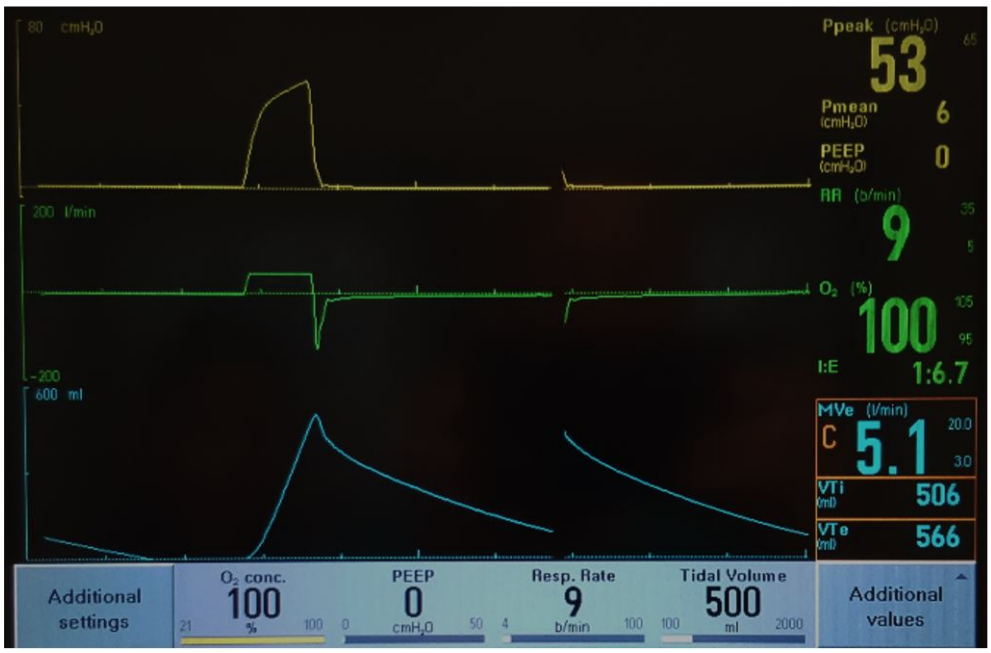
During expiration, gas flow out of the lungs is a passive process, and therefore depends on the pressure generated by the recoil of the chest wall and lung tissue. That's not much pressure. In the presence of significant airway resistance (eg. in asthma or bronchospasm of COPD) this pressure is inadequate to empty the lungs in a reasonable period of time. There's not much you can do about the elastic recoil of the chest wall and lungs, and often little you can do about the bronchospasm; which means that the expiratory time is the only variable you can manipulate to help matters. By increasing the I:E ratio (and allowing a longer expiratory time) one allows the last dregs of the tidal volume to escape, taking filthy CO2 with it.

Decreasing the I:E ratio (eg. to 1:3, 1:4 and beyond) has the following expected effects:

- Increasing clearance of CO2 by increasing the time available for passive expiration
- Decreasing gas trapping and "auto-PEEP" by the same mechanism
- Poorer oxygenation because of decreased mean airway pressure (though this is usually offset by the intrinsic PEEP which is usually seen in these settings
- Decreased haemodynamic impact of positive pressure (also because of decreased mean airway pressure)



In reality, the flow curve is rarely useful because the automatic scale is usually unhelpful. To accommodate the inspiratory flow rate, the scale ends up being high (in the graphic below it goes up to 200L/min). Because these sorts of strategies are usually employed for patients with severe bronchospasm, expiratory flow rates are usually much lower than that, which makes the expiratory flow curve comparatively flattened. The volume/time graphic, however, is illustrative. The tidal volume here is clearly taking its sweet time on the way out.



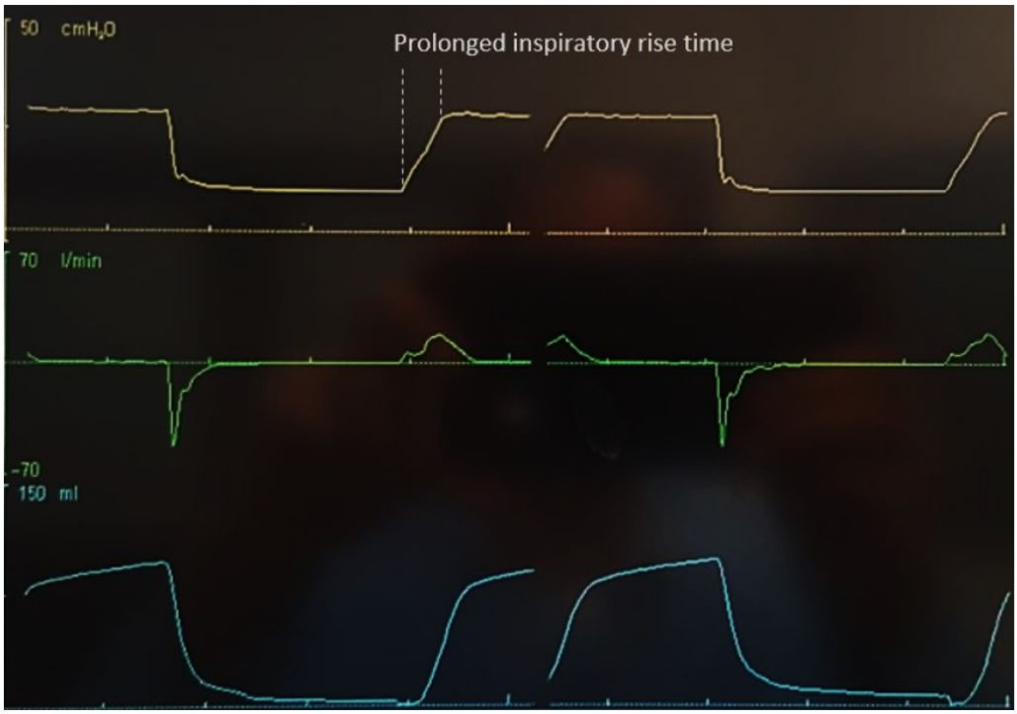
In case you are wondering, most ventilators will allow you to set truly insane I:E ratios. For instance, the SERVO-i will deliver an I:E ratio of 1:10. Literature

supports the use of such perverse ventilator settings. Brown (2007) recommends 1:7; Ahmed et al (2015) are more conservative with 1:3 to 1:5. Laher & Buchanan (2017) give 1:4 to 1:5. Nobody recommends 1:10, nor is there any literature exploring these extremes.

Inspiratory rise time

Of the various ventilator settings subjected to intensivists' fiddling, the inspiratory rise time is the least frequently fiddled with. Perhaps this is because the utility of adjusting this setting is fairly obscure and rarely does a situation arise which calls for dramatic changes to this variable. Or, rather, rarely are dramatic changes to this variable useful, in any meaningful sense.

In short, the inspiratory rise time determines the rate at which the ventilator achieves a target pressure (in pressure control and pressure support modes) or flow rate (in volume control modes). It is set in percent of the breath cycle (from 0% to 20% of the breath cycle time) or in seconds (0-0.4 seconds). The default settings are usually 0.15 seconds or 5%.

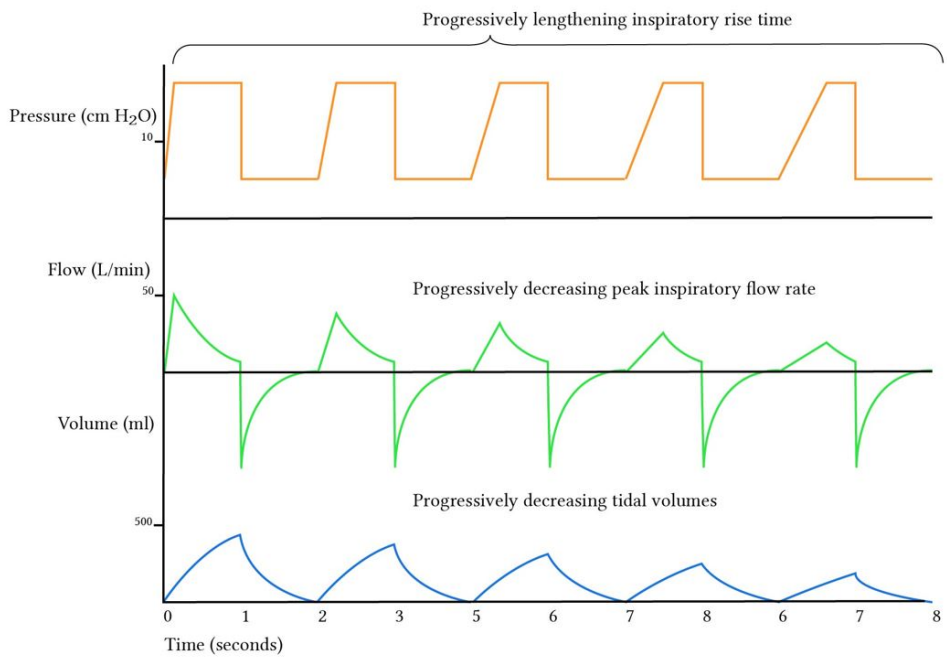


In summary, in a pressure controlled mode, the consequences of a prolonged respiratory rise time are:

- Decreased inspiratory flow rate
- Slower recruitment of alveoli
- Lower tidal volume delivered on a pressure control mode
- Increased work of breathing
- Decreased patient comfort

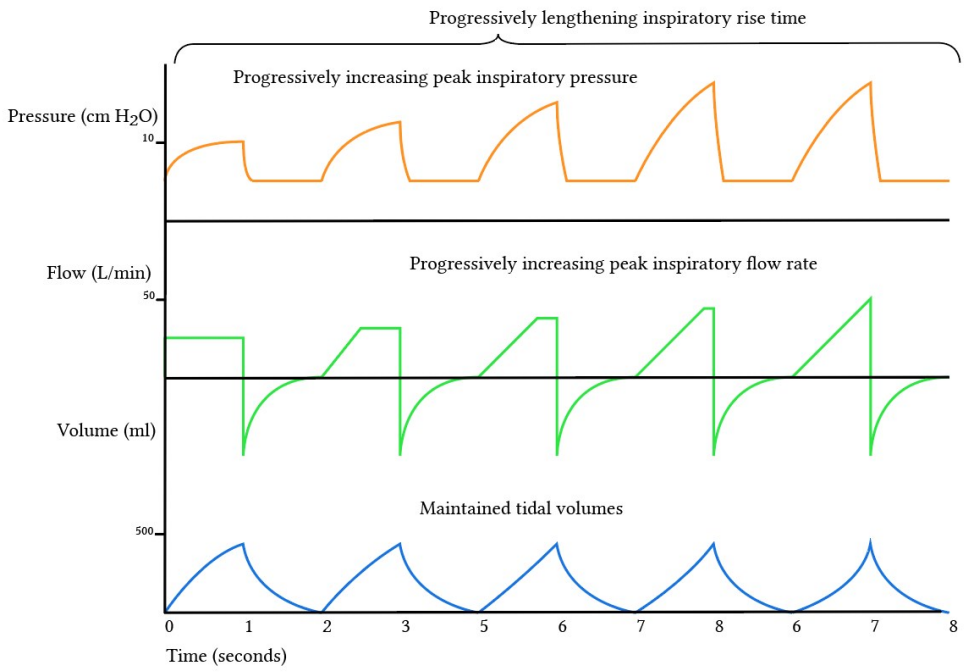
The consequences of a shortened respiratory rise time are

- Increased flow rate
- Increased airway resistance contribution to peak airway pressure
- Higher peak airway pressures, particularly in conditions with airflow limitation
- Decreased work of breathing during inspiration



In a volume control mode, if the inspiratory rise time is prolonged, the ventilator will increase flow more slowly to achieve the target tidal volume later in the breath.

Logically, as flow is volume over time, the same area under the curve needs to be maintained (if the respiratory cycle time remains unchanged); i.e. in order to achieve the same tidal volume, the ventilator needs to blow more flow later in the breath if it was limited to blowing slowly in the beginning. And because pressure is the product of flow rate and resistance, the higher the final flow rate, the higher the final peak airway resistance. Observe:



Thus:

In a volume controlled mode, the consequences of a prolonged respiratory rise time are:

- Increased inspiratory flow rate
- Reduced recruitment of alveoli (long time constant alveoli will not get recruited)
- Higher pressure required for the same tidal volume

The consequences of a shortened respiratory rise time potentially could be:

- Decreased patient comfort, if the patient is experiencing "flow starvation" (but really what they need is just a bigger tidal volume, or just to go on a patient-triggered mode
- A lower peak inspiratory flow and peak inspiratory pressure

In general, in the normal world where everybody is using some kind of square pressure waveform mode, inspiratory rise time should be left short, whenever one has any control over it. This gives the highest possible flow early in the breath, which is what the patients seem to want. Brouwer et al (2006) found that spontaneously breathing patients on a pressure-support mode of ventilation were much more comfortable with faster flow rates and shorter rise times, and Chiumello et al (2003) demonstrated that their inspiratory work of

breathing was significantly reduced. Volume, being a product of flow and time, also favours higher flow rates – and therefore in a pressure controlled mode the tidal volumes will decrease with slower rise times and lower flow rates

So, why would you ever want to have a prolonged inspiratory rise time? Well. Theoretically, the flow rate and the airway resistance are quite tightly linked, i.e at high flow rates the peak airway pressure will be high in bronchospastic patients because of the increased resistance to flow. Therefore, reducing the flow rate should reduce the peak airway pressure. However, this seems to be a fairly theoretical concept. In practice, one simply uses a mode of ventilation where the flow rate is low and stable, like volume control. One of the advantages of using a volume-controlled mode for such severe asthmatics is that the flat stable flow rate is less likely to trigger the overpressure alarms.

One further possible advantage of a slower rise time was once thought to be improved sputum clearance. Though it is not obvious from the literature, the rationale for this seems to be the concern that super-rrapid inspiratory flow can blow sputum plugs backward in the respiratory tree, thereby diminishing the rate of mucociliary clearance. Chapman et al (2018) tested this in the most artifical way possible, by snotting up some clear plastic tubing with simulated sputum (of two different viscosities) and observing its displacement during the operation of an artificial lung. The investigators came to the conclusion that beyond 5%, lengthening the inspiratory rise time has no beneficial effect on sputum movement.

Previous chapter: Selecting and adjusting PEEP

Next chapter: Modes and targeting schemes of mechanical ventilation

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